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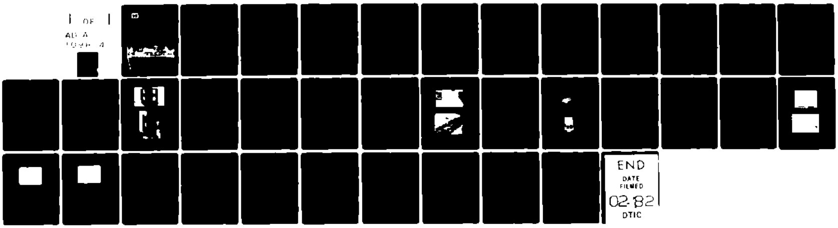

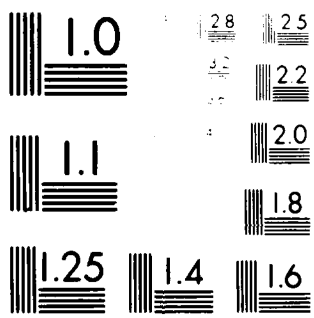

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DEVELOPMENT OF PROCEDURES FOR NONDESTRUCTIVE TESTING OF CONCRETE STRUCTURES

Report 3

FEASIBILITY OF IMPACT TECHNIQUE FOR MAKING RESONANT FREQUENCY MEASUREMENTS

by

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Development of the resonant frequency technique as a method for evaluation of concrete structures is in progress. It is desirable that structures be evaluated in place, nondestructively, and in real time. The availability of digital Fourier analyzers and mathematical functions such as spectra, coherence, and transfer relationships permits the analysis of the behavior of large structures under dynamic conditions in place and in real time. An impact system has been

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20. ABSTRACT (Continued).

tested which was proven more economical and versatile than the sinusoidal system currently in use.

With transient loading, all frequencies are applied to the structure simultaneously rather than being swept through one at a time. Because the resonant frequency of a structure is directly related to its dynamic Young's modulus and hence its mechanical integrity, the resonant frequency technique is useful in the field as well as in the laboratory. Factors that influence the soundness and safety of a structure, such as modulus, continuity, and boundary conditions (i.e. foundation and other restraints) also directly affect the resonant frequency. Some limited work has been done with both mathematical and physical modeling to develop measurement criteria that will improve prediction of the expected resonant frequency for structures with varying geometries and varying degrees of foundation restraint. The characteristic vibrational signature of a structure may be evaluated at selected time intervals in an effort to predict service life. Improvement in modal analysis and prediction of frequencies by mathematical modeling is needed. Field work has demonstrated the feasibility of the technique.

PREFACE

The work described herein was performed to develop an impact technique for making in situ, real-time resonant frequency measurements on large concrete structures in service in the Civil Works program of the Corps of Engineers. The report discusses feasibility of this technique. The study forms part of Work Unit 31553, Maintenance and Preservation of Civil Works Structures. The principal investigator for Work Unit 31553 is Mr. J. E. McDonald; the OCE technical monitor is Mr. Fred Anderson (DAEN-CWE-DC).

This report is the third in a series of reports giving results of studies to develop, adapt, and improve methods of nondestructive testing of concrete structures. Experimental work was begun at the U. S. Army Engineer Waterways Experiment Station (WES) in January 1979 to develop the resonant technique using the mechanical impact method of excitation. The initial work consisted of tests on small laboratory beams using a spectrum analyzer to determine fundamental resonant frequencies. In February 1979, it was found that the resonant frequencies could be measured on large concrete blocks of more than 10 tons mass and the dynamic modulus calculated. The technical development was performed by A. Michel Alexander. In July 1979, Dr. Carl Pace and Mr. Roy Campbell provided assistance in measuring resonant frequencies on the piers of the Lake Superior Compensating Structure in Sault Ste. Marie, Michigan. Mr. Henry Thornton assisted in the development in various significant ways.

This report was written by Mr. Alexander. The work was performed under the direct supervision of Mr. Billy Sullivan, formerly Chief, Engineering Physics Branch, Engineering Sciences Division, Concrete Laboratory (CL), and under the general supervision of Mr. John Scanlon, Chief, Concrete Technology Division, Structures Laboratory (SL); Mrs. Katharine Mather, formerly Chief, Engineering Sciences Division, CL; and Mr. Bryant Matner, Chief, SL, WES.

The Commanders and Directors of WES during this investigation and the preparation of this report were COL John L. Cannon, CE, COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE. Technical Director was Mr. F. R. Brown.

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A

CONVERSION FACTORS, INCH-POUND TO METRIC (SI) UNITS OF MEASUREMENT

Inch-pound units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	0.0254	metres
square inches	0.00064516	square metres
inches per second squared	0.0254	metres per second squared
feet	0.3048	metres
cubic yards	0.764554858	cubic metres
pounds (force)	4.448222	newtons
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (force) per square inch (psi)	0.006894757	megapascals

DEVELOPMENT OF PROCEDURES FOR NONDESTRUCTIVE TESTING OF CONCRETE STRUCTURES

Feasibility of Impact Technique for Making Resonant Frequency Measurements

PART I: INTRODUCTION

Background

1. With the decline in new construction starts in recent years, many of the older Civil Works hydraulic structures of the Corps of Engineers are having to continue in operation well beyond their original design service life. Consequently, evaluation and rehabilitation have assumed increased importance, as evidenced by the number of requests for assistance the Structures Laboratory (SL) has received from field offices during recent years.

2. The evaluation of Civil Works concrete structures generally involves extensive core drilling of the structure and foundation with subsequent laboratory testing of the cores obtained. In some cases such an approach is difficult, if not impossible. In all cases it is expensive and destructive. Unfortunately, nondestructive dynamic measurements using the common swept-sine method are not much better, since this method requires bulky and expensive equipment. The SL has successfully evaluated small laboratory concrete specimens by the resonant technique for many years; therefore, an effort was made to extend this approach to large structures. Also, the recent development of computerized real-time Fast Fourier Transform analyzers (FFT's) has opened the way for dynamically analyzing the structural behavior of locks and dams and other structures nondestructively and in place. The advantages of the impact system evaluated in this study are significant. Measurements are improved due to portability, cost, speed of measurement, and increased capability. Although there is room for development of measurement criteria, the

resonant technique using the impact type of excitation shows promise for the evaluation of large Civil Works structures.

3. Initially, the plans involved making resonant frequency measurements with the sinusoidal technique. Because of cost restrictions and other reasons, this technique was abandoned. Because of work done in the laboratory using a spectrum analyzer to measure fundamental resonant frequencies of small freezing-and-thawing test specimens (3-1/2 by 4-1/2 by 16 in.*) by the impact method, it was decided to attempt this on large rectangular blocks weighing several tons. This was successful, as the impact method gave the same resonant frequencies as the sinusoidal method. Again because of experience gained in calculating the dynamic modulus of elasticity of freezing-and-thawing test specimens using the equations of Pickett (Pickett 1945), we were successful in calculating the dynamic modulus of the large blocks using the measured resonant frequencies. The recent advent of the new digital computerized Fast Fourier Transform analyzers made it possible to make powerful mathematical calculation of functions such as spectrums, transfer relationships, coherence, and many others onsite and in real time. Also, all data can be stored on magnetic tape and analyzed at the laboratory.

Purpose

4. The objective of this investigation was to evaluate the feasibility of using the resonant frequency technique with impact excitation for in situ evaluation of the degree of deterioration, hence integrity, of large concrete Civil Works structures.

Scope

5. This investigation includes both a study of the feasibility of the resonant technique for determining the integrity of a field structure and a study of the feasibility of using the impact technique

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* A table of factors for converting inch-pound units of measurement to metric (SI) units is presented on page 4.

to excite the structure rather than the sinusoidal or swept-sine technique. This report deals primarily with the laboratory and field work associated with measurements made at Sault Ste. Marie on eight concrete piers of a dam across the St. Mary's River. The piers were modeled mathematically by modifying them to be rectangular so that Pickett's equations (Pickett 1945) could be used to estimate the fundamental frequency and then, having measured the actual frequency, to calculate the dynamic modulus. A rough physical model was constructed with ends sloped similar to the piers and was later attached by adhesive to a rigid surface to simulate the rigidity of the foundation at Sault Ste. Marie.

PART II: DEVELOPMENT OF RESONANT AND IMPACT TECHNIQUE

Principle

6. Traditionally, most measurements made of resonant frequencies of concrete structures in place have been made in order to be able to avoid destructive motions. Dampeners or stiffeners are added at critical locations after determining the mode shape to eliminate or to highly dampen the motion. On the positive side, however, all resonances are not dangerous and can even be beneficial when used to determine the mechanical behavior of the structure. The resonant frequency is a very sensitive indicator of a change in the dynamic modulus of a structure and its boundary conditions.

7. By exciting a structure with forces and observing the resulting motion, one can derive information useful in estimating the integrity of the structure. No assumptions as to modulus of elasticity, continuity, and foundation properties need be made. The resonant technique is not a localized test like coring. The resonant technique is a measurement of the total structure, including the surrounding foundation and supports. By exciting structures at forces below that level that is destructive, the mechanical behavior of the structure can be determined. The vibration characteristics of a "good" structure will differ from that of a "poor" structure.

8. The elastic properties of a specimen are directly related to the fundamental resonant frequency. Pickett's equations show that there are various factors that are related to the resonant frequency. They are the Young's modulus of elasticity, the geometry, and the boundary conditions. In tests of specimens the geometry and the boundary conditions are controlled. All laboratory specimens are either prismatic or cylindrical. When tested, the specimens are supported at nodes or points of little or no vibration so as to minimize the draining of the excitation energy into the supports, resulting in higher signal levels with low damping. This technique allows the specimen to vibrate freely with minimum restraint in a free-free mode. Young's dynamic modulus of elasticity

or the modulus of rigidity can be calculated from the resonant frequency according to ASTM Designation: C 215 (CRD-C 18), a procedure that has been a national standard in the United States since 1947.

9. In the past, sinusoidal excitation has been used in a number of applications by the aircraft and automobile industries to measure resonant frequencies. This was the only technique available for measurement of resonant frequencies of freezing-and-thawing test specimens until now. With the recent advent of the new digital systems for making Fast Fourier Transforms of force and acceleration signals, a system can now be excited with a transient or one-shot force pulse rather than the slow technique of sinusoidal waves. There are considerable advantages of the FFT over traditional sine-wave systems. All analyses can be done onsite, as the computer contained in the system is programmed for calculating appropriate mathematical functions in real time. With the sine-wave systems, the records were brought back to the laboratory and the various mathematical functions calculated. Functions such as coherence, auto and cross power spectrum, impulse response, auto and cross correlation, transfer, and other measurements are possible with the FFT onsite. The advantage of obtaining a full analysis of data onsite is obvious. With nearly instant feedback of the structure's behavior, better decisions can be made from one measurement to the next about how to get the most information from the structure by more intelligent placing of the transducers over the structure.

10. Another significant feature of the FFT is the capability to store all data for later analysis quickly and easily with magnetic storage. The enhancement of poor signals is a plus, as many signals can be added until the noise is canceled. Many types of plots are possible, such as magnitude, phase, real, imaginary, nyquist, and other variations. All are instantly presented on the screen by the push of a button.

11. The main feature of the FFT is the capability to analyze impact tests. A single impact is applied to the structure, and the dynamic behavior is obtained in a few seconds. All frequencies are present simultaneously rather than being swept through one at a time with the sinusoidal technique. The equipment is much more portable, as large shakers

with large power generators that supply energy in the kilowatt range are not required. The FFT can be powered with a small gasoline-powered generator of less than one kilowatt.

12. An impact load pulse contains a wide spectrum of frequencies. By varying the type of impact pad used and the size and weight of the impactor, the range of the frequencies can be varied. If the structure is to be vibrated at a low frequency, a softer pad can be used. A harder pad will generate higher frequency energy. The structure should be studied mathematically to obtain an idea at what frequencies the desired modes of vibration exist. By choosing the correct type of impactor, a structure can be resonated at the fundamental frequency of resonance without unwanted resonances at other frequencies. A spectrum should be obtained with each impact to determine the frequency content of the energy delivered to the structure.

Description of Laboratory Tests

13. Sinusoidal vibration and impact tests made to determine the resonant frequencies on some large rectangular blocks at the laboratory have produced some interesting findings (see Figures 1 and 2). The resonate technique is used to determine the elastic qualities of a structure as a whole. This is different from compressional wave velocity measurements which give only the dynamic modulus of the concrete averaged along the path between the transmitter and receiver, and not the modulus of the total structure.

14. Initially, a complex sinusoidal mechanical impedance system was used. This system was used to measure the resonant frequencies, damping, and the various transfer functions of impedance, compliance, inertance, etc., of the large rectangular blocks.

15. Because the labor cost and time required were anticipated to be great, another system was sought. This new system used an impact hammer to develop one pulse rather than the continuous sinusoidal vibration. By use of a spectrum analyzer, the resonant frequencies were measured

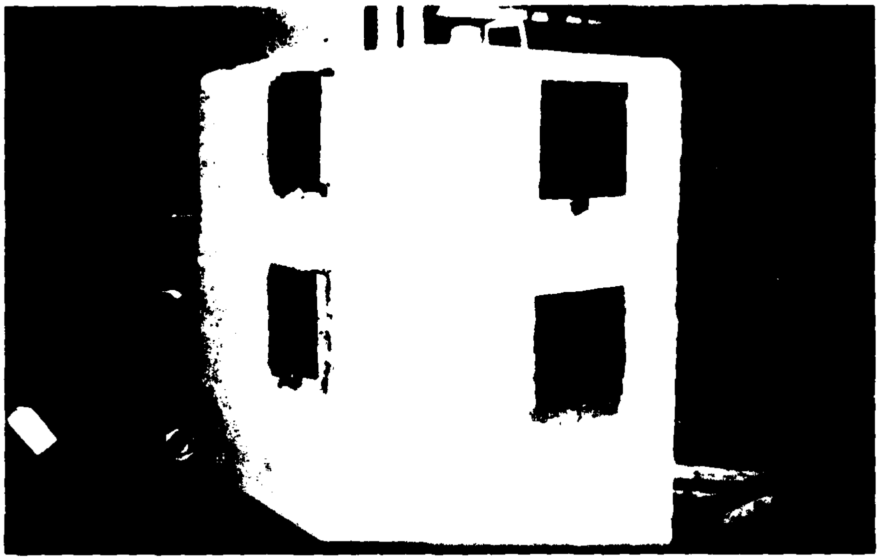


Figure 1. 3- by 6- by 6-ft block

Figure 2. 3- by 6- by 10-ft block

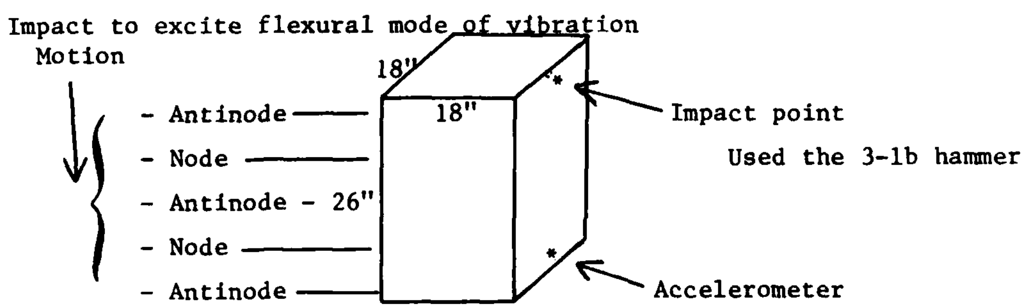
much more quickly and simply. This equipment is much more portable and much less expensive than that for the other system.

16. The most significant finding at this stage was the discovery that the dynamic E of structures can be calculated from the measurement of the fundamental resonant frequency of vibration. The dynamic E is a measure of the elastic qualities of a material which have to do with velocity of wave propagation, shear modulus, Poisson's ratio, etc. With the fundamental frequency equations of Pickett, the dynamic E of small or large laboratory specimens of a rectangular or cylindrical shape can be calculated.

17. The following calculations of the dynamic E of the large structures* from a measurement of the fundamental resonant frequency of vibration are shown. For an explanation of equations, see Pickett's equations (Pickett 1945).

Structure	Mass, lb	Measured Resonant Frequency, Hz	Calculated Dynamic E, psi
(a) 18 in. by 18 in. by 26 in.	765	2280	5.84×10^{-6}
(b) 3 ft by 6 ft by 6 ft	16,800	564	3.54×10^{-6}
(c) 3 ft by 6 ft by 10 ft	28,140	322	5.73×10^{-6}

(a) Mass = 765 lb



* Both large blocks were part of a slipform investigation. Technical Report C-74-3 by K. L. Saucier, "Laboratory Investigation of Slipform Construction for Use in Mass Concrete Structures," July 1974, describes that investigation.

where:

t = dimensions in inches in the driven direction

K = radius of gyration

$$K = \frac{t}{3.464} = \frac{18''}{3.464} = 5.196$$

$$\frac{K}{L} = \frac{5.196}{26''} = 0.2$$

From Table, $T = 3.58$ when $\frac{K}{L} = 0.2$

$$C = 0.00245 \frac{L^3 T}{bt^3}$$

$$C = 0.00245 \frac{26^3 \cdot 3.58}{18 \cdot 18^3}$$

$$C = 0.0014685$$

$$E = CWn^2 \qquad n = 2280 \text{ Hz as measured}$$

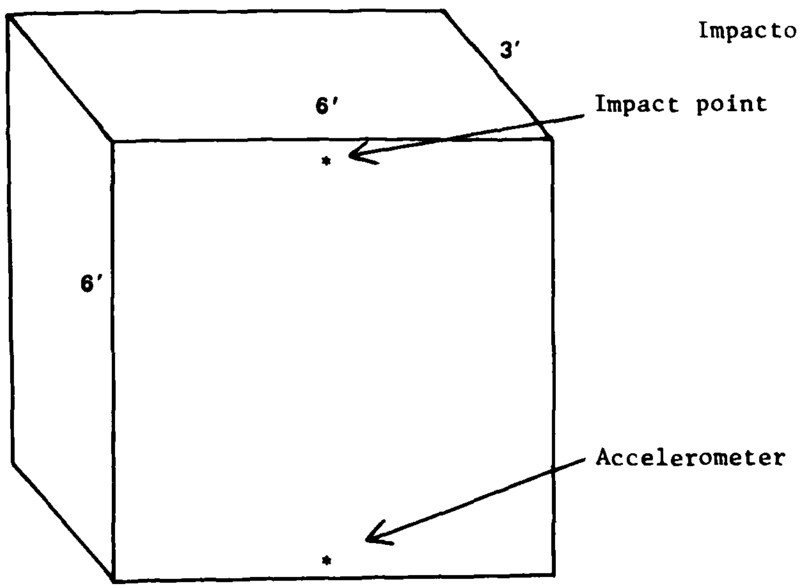
$$E = (0.0014685)\ 765\ (2280)^2$$

$$E = 5.84 \times 16^6 \text{ psi}$$

(b) 3- by 6- by 6-ft block

Weight = 16,800 lb

Impactor: 26-lb lead weight



$K = \frac{t}{3.464} = \frac{3 \cdot 12}{3.464} = 10.393$

$\frac{K}{L} = 0.14434$

$C = 0.00245\frac{L^3T}{bt^3}$

$C = \frac{(0.00245)(6 \cdot 12)^3 2.434}{6 \cdot 12 \cdot (3 \cdot 12)^3}$

$C = 0.00066259$

From Table

$0.14 \longrightarrow 2.36$

$0.144 \qquad T$

$0.16 \longrightarrow 2.73$

$T = 2.36 + (2.73 - 2.36)\frac{(0.144 - 0.14)}{0.16 - 0.14}$

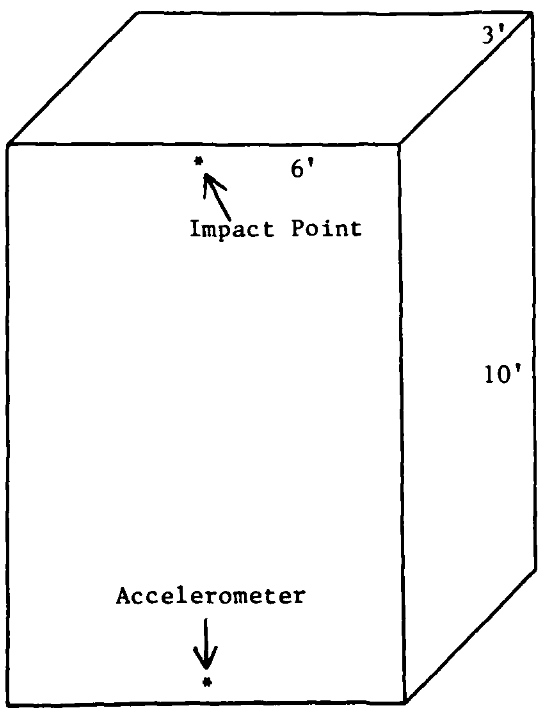
$T = 2.434$

$E = CWn^2$ Measured resonant frequency

$E = (0.00066259)16{,}800(564)^2$

$E = 3.54 \times 10^6$ psi

(c) 3- by 6- by 10-ft block



Weight - 28,140 lb

Impactor - 26-lb lead weight

$K = \frac{t}{3.464} = \frac{3 \cdot 12}{3.464}$

$K = 10.3926$

$\frac{K}{L} = \frac{10.3926}{10 \cdot 12} = 0.0866$

From Table

$0.08 \longrightarrow 1.48$

$0.0866 \qquad T$

$0.09 \longrightarrow 1.60$

$$C = (0.00245)\frac{L^3T}{bt^3}$$

$$C = \frac{(0.00245)(10\cdot 12)^3 1.5592}{6\cdot 12(3\cdot 12)^3}$$

$$C = 0.001965$$

$$T = 1.48 + \frac{0.0866-0.08}{0.09-0.08}(1.60-1.48)$$

$$T = 1.5592$$

$$E = CWn^2$$

$$E = (0.001965)28140(322)^2$$

$$E = 5.73 \times 10^6 \text{ psi}$$

18. As shown by the calculations, the structure having a mass of 16,800 lb had a low dynamic E. This specimen had a number of large cracks in it. Some of them were visible. Although the largest block (3- by 6- by 10-ft) appeared sound, the smaller block (3- by 6- by 6-ft) had visible cracks. At the time the blocks were constructed, two batches used to make the smaller block had 4-1/2- and 6-in. slumps. Both blocks had the following composition:

Cement - Type II portland, RC-658, 183 lb/cu yd
Pozzolan (fly ash) AD-3(11), 78 lb/cu yd
Aggregate - 6-in. nominal maximum size, crushed limestone
Fly ash content - 35 percent
Water/cement + pozzolan = 0.62 by mass

The other block (18- by 18- by 26-in.) is a support; no data on the concrete in it are available.

Description of Field Test

19. A photograph of the FFT is shown in Figure 3. The metal A-frame with a manually-operated winch that supports the impactor is shown in Figure 4. The impactor is pulled back and allowed to swing over a 2- or 3-ft arc striking the reaction block which is bolted to a metal plate that is secured to the concrete structure to be tested by metal anchors and epoxy. A load cell secured to the front of the impactor measures the load pulse. The response of the structure is detected by an accelerometer placed at a suitable location. The FFT was a dual channel unit

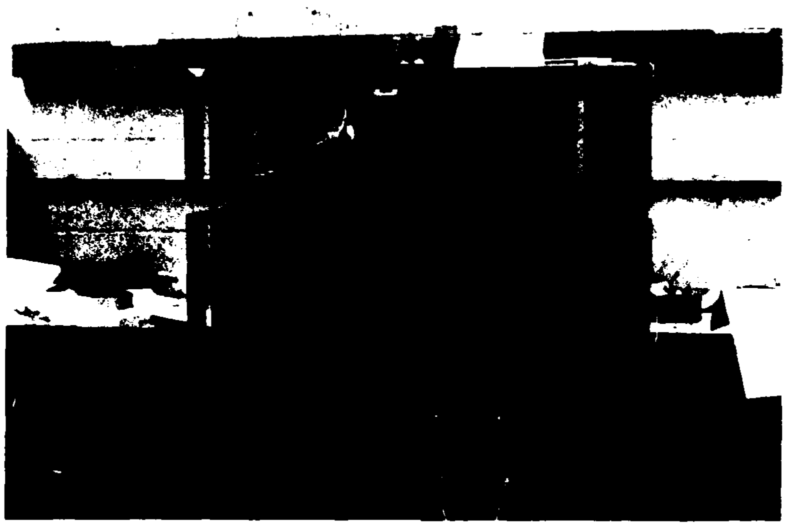


Figure 3. Real-time Fourier transform analyzer processes load pulse signal and resulting free vibration from hammer impact

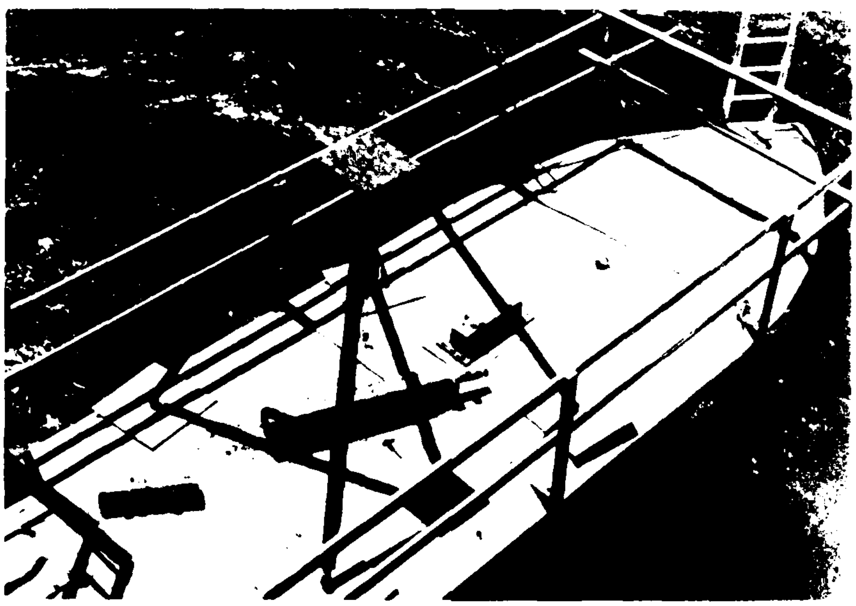


Figure 4. System to generate load pulse: A-frame, 550-lb impactor, load cell with impact pad, reaction block, and steel plate

with the capability to process a force and acceleration signal. Mechanical impedance and resonant frequency values were taken during each test. Although Figure 4 shows the setup for longitudinal measurements, it was determined that no sharp resonance could be found when tests were made in that direction. All the piers were later measured in the flexural mode by swinging the impactor in a direction perpendicular to the pier. Previous measurements in the laboratory had verified that small concrete specimens could be driven from the surface and the response measured from the surface, obtaining the same resonant frequencies as when the specimen was driven in the center of the side and the response measured on the center of the opposite side. It would have been very difficult to drive the pier from the side, as a barge would have been required to support men and equipment, sometimes in swift water current when the gates were open. Also, a barge impacting against the pier would have created noisy acceleration signals.

20. The steel plates used to bolt the reaction block were installed in the following manner. First, the concrete surface was roughened over an area sufficient to contain the 1-1/2-ft by 3-ft by 3/4-in. plate. Then 14-1/2-in. holes were drilled into the concrete. An adhesive was then spread over that surface and 1/2-in. anchor bolts were used to secure the steel plate to the concrete. The reaction block could then be bolted down to the steel plate after allowing at least one day for the epoxy to cure.

21. Figure 5 shows the force gage with signal conditioning. The impact pad, gage, and head bolts to either of the large impactors are shown in Figure 4. Figure 6 shows the accelerometers and signal conditioning equipment. A description of the piers is given by Thorton et al. (1980).

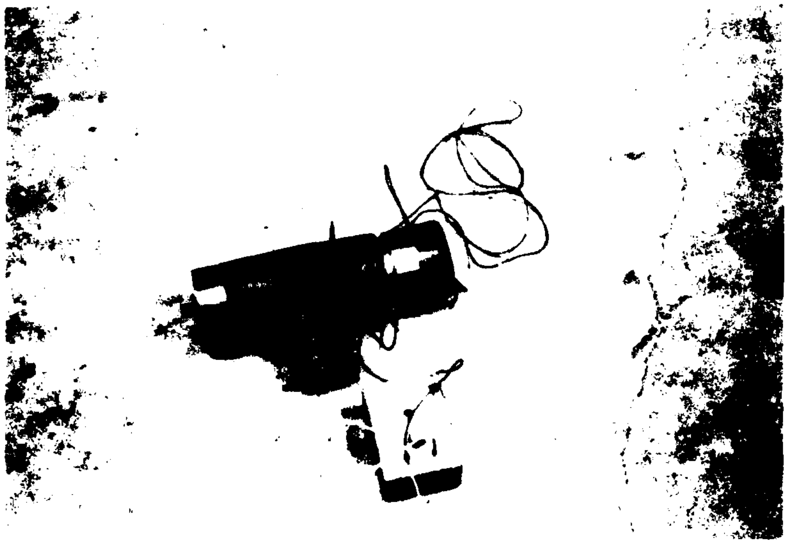


Figure 5. View of the load cell and power supply used to measure impact force

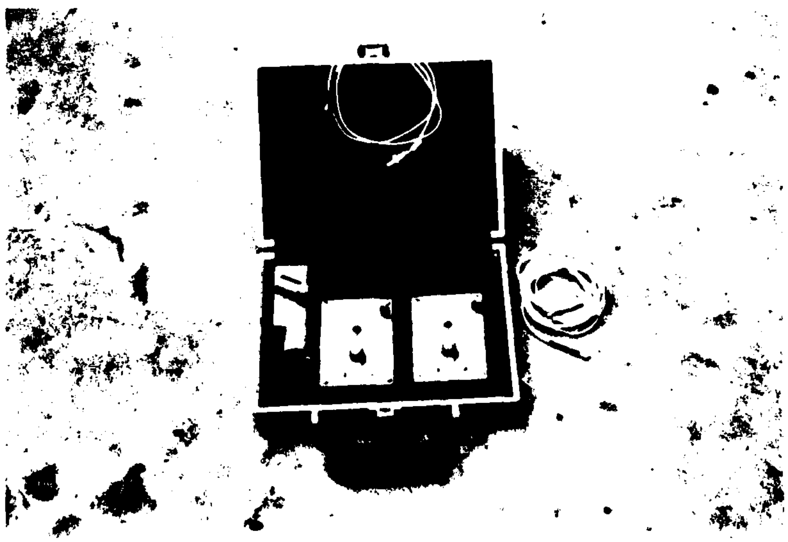


Figure 6. Accelerometers, power supplier, and cables for measuring resonant frequencies

PART III: DISCUSSION AND RESULTS

22. Every type of impact waveform will have a different frequency content. A force pulse from an impact with a small hammer will have a high frequency content. It might contain energy from 0 up to 10,000 Hz or more. A 12-lb sledge hammer will generate energy from 0 Hz up to around 1500 Hz. A 550-lb weight, such as the one used in the work referenced previously, might not generate any energy over 200 Hz when a hard rubber pad is used for the impact surface. The energy level, however, will be increasingly higher for each case mentioned. If a structure has a resonance at 300 Hz, it would not respond by being excited with an impact whose frequency content does not contain energy at 300 Hz. It is, therefore, important that the frequency spectrum of each force pulse is measured before making a measurement, as the frequency characteristics of the hammer and structure must match each other. Also, it is advantageous not to generate energy above the frequencies of interest in the structure, as the excess energy is being used to excite resonances that are not wanted. It becomes noise for all practical purposes that can introduce confusion. It also leaves less energy available to excite the desired resonances.

23. Other possible unwanted resonances could come from the metal reaction block that the impactor strikes. Tests made with the accelerometer on the block, however, showed that there were no resonances from 0 to 400 Hz, which more than covered our measurement range. The accelerometer and force cell had resonances up in the kilohertz range well outside the range of measurement.

24. Another step that should be carried out prior to measurement is the mathematical or physical modeling, or both. This will give an approximate frequency that will prevent a great deal of analyzing. It will not give the exact frequency but will permit establishment of the range without a lot of trial and error on the structure. Pickett's equations were programmed for the computer so that various parameters could be altered to determine the effect of each parameter on the resonant frequency (see Appendix A). As previously mentioned, the effects

of the foundation restraint and geometries could not be calculated for other than a rectangular model. However, some useful information was determined by testing a physical model in the laboratory. A standard freezing-and-thawing specimen (3-1/2- by 4-1/2- by 16-in.) was measured in the flexural mode similar to the piers studied in the field. It measured 1635 Hz. Using the computer program, the dynamic modulus calculated to 3.75 million psi. The ends of the beam were then sawed to points to simulate the piers in the field. The frequency then measured 2163 Hz. By determining the mass of the sawed specimen and assuming it to be rectangular, the average length of the specimen was calculated to be 13.59 in. Using the same dynamic modulus as above, the predicted frequency calculated to be 2173 Hz. This is only 1/2 percent from the actual measurement. Therefore, even though the piers are not rectangular, a rough estimate of the frequency is possible by calculating the weight of the pier and calculating an average rectangular length. The average length of the smaller piers was calculated to be 43.32 ft. Substituting this into Pickett's equations and using a dynamic modulus of 8 million, the frequency is found to be 60.6 Hz. The actual frequency measured on the piers averaged 76.44 Hz.

25. Also, the effect of the foundation must be considered restraint since the pier cannot be measured in a free-free mode. The small beam was bonded to a rigid concrete base to determine the effect of the restraint on the resonant frequency. As a result, the resonant frequency increased from 2163 Hz to 2225 Hz. This increase in frequency of the model agrees with the higher frequency measured on the piers but not to the degree necessary to coincide with the calculated value of 60.6 Hz. The 3 percent increase in the physical model would only represent about 2 Hz more, or 62 Hz, in the expected frequency for the piers. So the best prediction from the physical model is still 20 percent short of the actual measurement. This is, however, very useful to estimate what to expect from the structure before actual testing, even though the scaling was not exact.

26. By entering various parameters into the computer program, the following was determined. Given fixed dimensions (length, width, and

thickness) as well as density (or mass) and dynamic modulus, a definite value of the resonant frequency can be determined (see Table 1). The resonant frequency can be increased by decreasing the length, increasing the width, decreasing the density, or increasing the modulus. The frequency is decreased by doing the reverse on each parameter. A change in height does not affect the frequency. It was seen that the physical model increased in frequency when the base was made rigid. This is probably equivalent to increasing the width of the specimen. If the width is increased 2 ft and the density is decreased 10 lb/ft^3, the resonant frequency calculates to 74.7 Hz. This is close to the average frequency of 76.44 Hz measured on the smaller piers. From coring tests made on the piers, the static modulus was found to average around 6.5 million psi, with some specimens going to 8 million. As the dynamic modulus usually runs higher than the static modulus, 8 million was chosen for the mathematical calculations. Also, other tests showed the density to be around 158 lb/ft^3 (Thornton et al. 1980).

27. The procedure for making the resonant frequency measurement involves positioning the A-frame so that the impactor supported by the winch can strike the reaction block in the direction perpendicular to the long axis of the pier. An impact pad is chosen to produce the correct frequency content so that the fundamental frequency will be excited in the flexural mode. One person can pull the 550-lb impactor back through a small arc and then direct it toward the reaction block with a smooth forceful push. Typically, the force pulse will peak at 5000 lb with the pulse existing for about 15 ms. A photograph of the measurement of force versus time is shown in Figure 7.

28. A typical linear spectrum of the force pulse shows that the energy is essentially flat from 0 to around 100 Hz and falls off sharply up to 1000 Hz. The spectrum is shown in Figure 8. A low stiffness impact pad was used on the front of the impactor and force gauge.

29. Although only resonant frequencies were needed for deterioration measurements, transfer function measurements were made so that the mechanical impedance could be determined. Figure 9 shows the ratio of the acceleration to the force. This is typical of all eight piers measured.

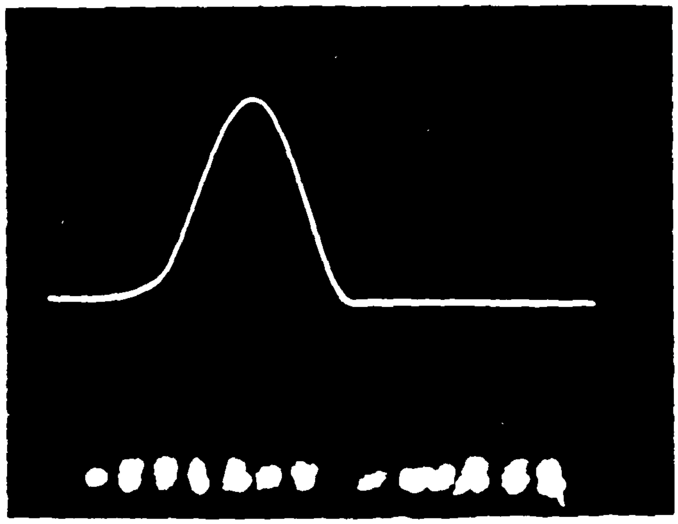


Figure 7. Force versus time

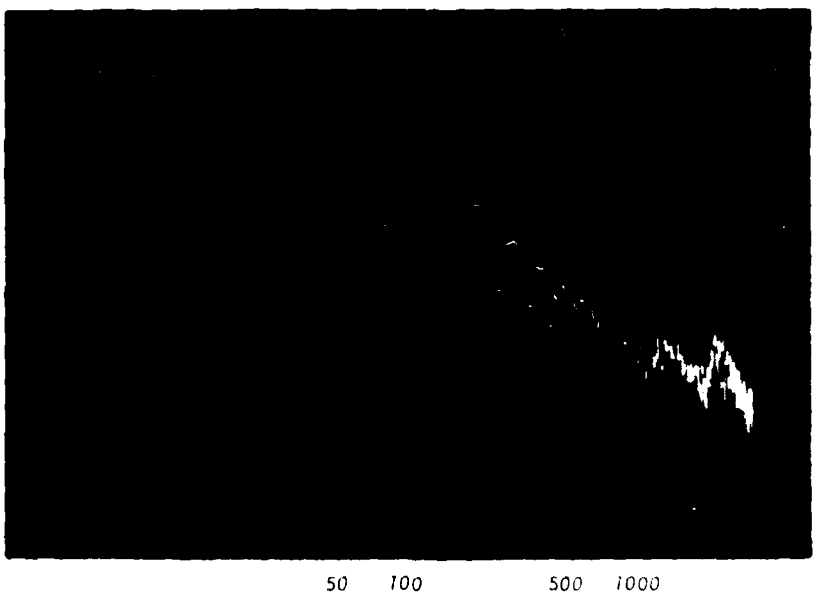


Figure 8. Force in frequency domain

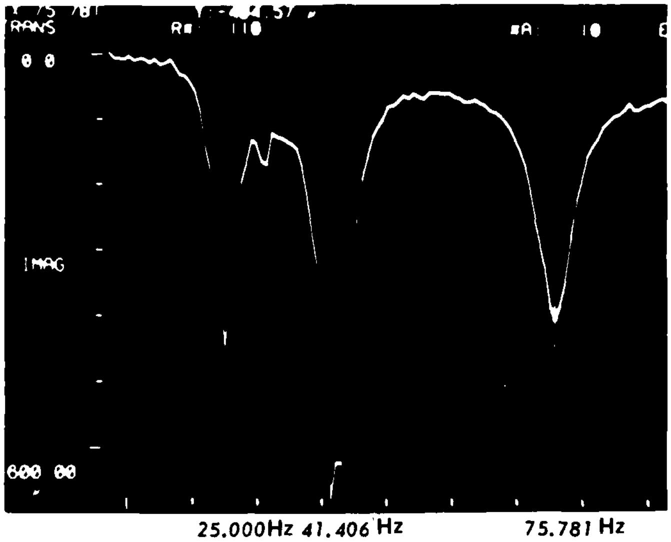


Figure 9. Ratio of acceleration to force
(measured at top of downstream end of pier)

The peak at 75.781 Hz represents the flexural frequency. The response was measured at the very top of the downstream end of the pier. In the flexural mode, there is an antinode at that location or point of maximum vibration. Figure 10 shows a measurement of the same pier but with the accelerometer moved to the center of the pier. At that location the motion will still be a maximum but will be moving opposite in phase to the end of the pier. When viewed on an imaginary plot, the peak goes up rather than down. Notice the resonance in the center of the photograph; it has almost vanished, indicating that the center of the pier happens to be a node for that particular mode of vibration. The fundamental resonant frequency for the torsional mode does produce a node in the center of a specimen; therefore, we can assume that this is probably the torsional mode. The 25-Hz resonance may be a subharmonic of the 75.781-Hz signal. It is too low to be the flexural. Although the particular FFT used does not have the modal analysis capability, the imaginary plot is still a method of determining mode shapes if enough work is done moving the accelerometer over the structure. As time was

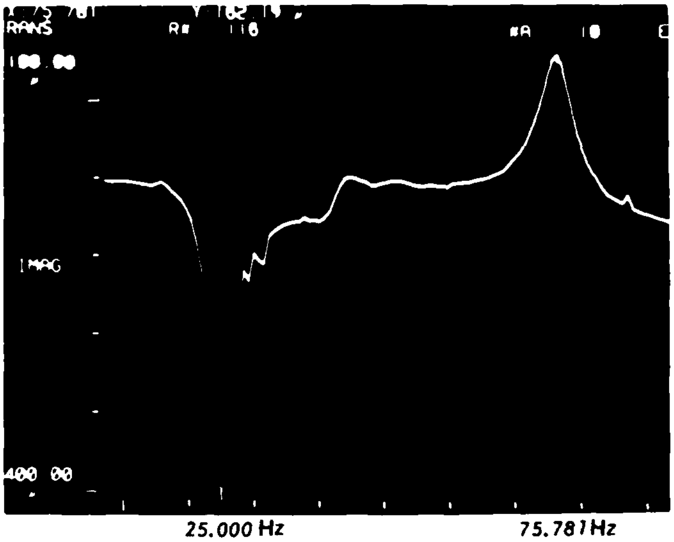


Figure 10. Ratio of acceleration to force
(measured at center of pier)

limited, exploration to accurately define each mode shape was not undertaken. However, the evidence is reliable that a resonance of about 76 Hz is the correct one for the smaller of the piers. More information on the results of the tests can be found in Thornton et al. (1980).

30. There was a sufficient signal-to-noise ratio for the frequency measurements. The sensitivity was good using a 50-g accelerometer and impacting the structure with 5000-7000 lbf of peak force. As the piers were narrow in the direction of the impact and long in the direction perpendicular to the impact, this resulted in a low stiffness and hence a good frequency measurement at resonance. All measurements were made in the flexural mode as the conditions were not good for the longitudinal mode.

31. The problems of long cables, electrical noise, magnetic fields, and other various sources of noise do not affect the measurement of frequency as they do the measurements of the amplitudes of currents and voltages. Hence the accuracy of the frequency measurements is primarily a function of the resolution of the dynamic analyzer. In the

100-hertz range, the range that covered our measurements, the accuracy was about 0.5 hertz. However, once the location of the frequencies are roughly known, the analyzer can be switched to the passband mode which permits a measurement at 75 hertz with an accuracy of 0.01 hertz. The accuracy of the force measurement is less than ± 5 lbf. Once it is determined that the level of the impact is satisfactory and the waveform of the impact is normal, the force measurement can be eliminated.

32. At present our mathematical modeling is limited to Pickett's equations, which only deal with rectangular and cylindrical structures. A small desk-top computer and a finite element software package can be purchased that will permit analysis on all shapes of structures. At present the technique is useful as a field inspection tool to monitor changes occurring in the structure. The determination of the absolute integrity of a structure from a single set of tests is not possible at present.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

33. The impact resonant frequency technique certainly shows promise for measuring the modulus of elasticity of the concrete in structures in place, or at least the change in modulus between readings.

34. The impulse technique permits making economical, quick, and accurate onsite analysis.

35. Continued progress on the resonant technique using impulsive loading may provide advances in the evaluation of older Civil Works structures and in dam safety.

36. It is recommended that work in the laboratory continues to develop the measurement criteria for nonrectangular geometries and for foundations that exhibit varying degrees of restraint. Because the resonant frequency is directly related to the modulus and foundation, it is important that this technique be developed in an effort to determine the mechanical integrity of a structure and hence aid in the prediction of its service life.

37. Resonant frequencies should be determined on structures at the time of construction. Having such data on each structure will permit the structure to be monitored yearly, as a change in the integrity will be seen as a change in the resonant frequency.

38. Although the technique is presently useful as an inspection technique to monitor mechanical changes in a structure, it is recommended that measurements of modal properties be used in conjunction with a more accurate mathematical model such as the finite element technique in hopes that in the near future measurement criteria can be developed that will permit predicting of the degree of deterioration of complex structures.

39. Because of the promise seen in this technique to monitor changes in structures with time, to monitor differences between structures exactly alike, and to monitor different points on long continuous structures of constant geometry, we have purchased an FFT housing modal analysis capability. Also, our plans are to purchase one of the

recently developed economical finite element packages that run on small desk-top computers in our continued research effort to predict the degree of deterioration for complex structures.

40. The work described is continuing; therefore, the final form of the technology transfer has not been decided. It is likely that this research will lead to procedures for evaluating the condition of structures in service and that these will be included in EM 1110-2-2002.

REFERENCES

Pickett, Gerald. 1945. "Equations for Computing Elastic Constants from Flexural and Torsional Resonant Frequencies of Vibration of Prisms and Cylinders," Bulletin 7, Research Laboratory of the Portland Cement Association, Skokie, Ill.

Thornton, Henry T., Jr. et al. 1980. "Evaluation of Condition of Lake Superior Regulatory Structure, Sault Ste. Marie, Michigan," Miscellaneous Paper SL-81-14, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Table 1

Mathematical Modeling

Input Parameters					Result	
Length ft	Width ft	Height ft	Dynamic Modulus 10^6 psi	Density lb/ft^3	Frequency Hz	Frequency Change Hz
Reference - input parameters for smallest piers						
43.32	8.0	22.0	8.0	158	60.6	--
Length increased by 1 ft						
44.32	8.0	22.0	8.0	158	58.1	-2.5
Width increased by 1 ft						
43.32	9.0	22.0	8.0	158	66.8	6.2
Decreasing height by one-half						
43.32	8.0	11.0	8.0	158	60.6	0
Decreasing density by 10 lb/ft^3						
43.32	8.0	22.0	8.0	148	62.6	2.0
Decreasing modulus by 1 million psi						
43.32	8.0	22.0	7.0	158	56.7	-3.9
Increasing width by 2 ft						
43.32	10.0	22.0	8.0	158	72.3	11.7
Increasing width by 2 ft and decreasing density by 10 lb/ft^3						
43.32	10.0	22.0	8.0	148	74.7	14.1
Increasing length by 5 ft and width by 1 ft, also equivalent to input parameters for larger piers						
48.32	9.0	22.0	8.0	158	54.7	-5.9

Smaller piers averaged 76.44 Hz
Larger piers averaged 62.750 Hz
13.69 difference

APPENDIX A: PRINTOUT FROM PROGRAM FOR CALCULATING RESONANT FREQUENCY

```
LIST

1000C    THIS PROGRAM WILL CALCULATE THE RESONANT FREQUENCY FROM
1010C    VIBRATION IN THE FLEXURAL MODE.ALSO THE VELOCITY IS
1020C    CALCULATED FROM THE FUNDAMENTAL RESONANT FREQUENCY.
1021C    SEE CRD-C 18-59 FOR FURTHER DETAILS.
1030C
1040C    VALUES OF CORRECTION FACTOR,T
1050C    -----------------------------
1060C        K/L          T
1070C    -----------------------------
1080C        0.00        1.00
1090C        0.01        1.01
1100C        0.02        1.03
1110C        0.03        1.07
1120C        0.04        1.13
1130C        0.05        1.20
1140C        0.06        1.28
1150C        0.07        1.38
1160C        0.08        1.48
1170C        0.09        1.60
1180C        0.10        1.73
1190C        0.12        2.03
1200C        0.14        2.36
1210C        0.16        2.73
1220C        0.18        3.14
1230C        0.20        3.58
1240C        0.25        4.78
1250C        0.30        6.07
```

```
1260C     ***********************************************
1270      CHARACTER A*1
1271      PRINT,
1272      PRINT,
1273  070 PRINT,"PROVIDE NUMBERS FOR FLEXURAL MODE CALCULATIONS"
1274      PRINT,
1275      PRINT,
1280      PRINT,"ENTER LENGTH OF SPECIMEN IN FEET OR END WITH 9999."
1290      READ,XLENGTH
1300      NTEST=XLENGTH
1310      IF(NTEST.EQ.9999)GO TO 080
1320      PRINT,"ENTER CROSS SECTION DIMENSION IN THE DRIVING
1330&  DIRECTION IN FEET"
1340      READ,TEE
1350      PRINT,"ENTER OTHER CROSS SECTION DIMENSION IN FEET"
1360      READ,BEE
1370      XK=(TEE*12.0)/3.464
1380      CC=XK/(XLENGTH*12.)
1390      PRINT,"K/L -",CC
1400      PRINT,"ENTER LOW AND HIGH VALUE ON EITHER SIDE OF K/L
1410& FROM THE TABLE"
1420      READ,CC1,CC2
1430      PRINT,"ENTER LOW AND HIGH VALUE OF (T) THAT CORRESPONDS
1440& TO THE K/L NUMBERS"
1450      READ,T1,T2
1460      T=T1+((T2-T1)*((CC-CC1)/(CC2-CC1)))
1470 PRINT,"T",T
1480      C=0.00245*(XLENGTH*12)**3.0*T/(((TEE*12)**3.0)*BEE*12.0)
1490 PRINT,"C",C
1500      PRINT,"ENTER DYNAMIC YOUNGS MODULUS-6000000 PSI IS TYPICAL
1510& FOR CONCRETE"
1520      READ,XMODULUS
1530 030 PRINT,"WANT TO ENTER WEIGHT OR DENSITY( W OR D )"
1540      READ 10,A
1550 010 FORMAT(A1)
1560      IF(A.EQ."W".OR.A.EQ."D")GO TO 20
1570      PRINT,
1580      PRINT,"CORRECT RESPONSE IS W OR D"
1590      GO TO 30
1600 020 IF(A.EQ."W")GO TO 40
1610      PRINT,"ENTER DENSITY IN LBS./CU. FT.-150.0 TYPICAL FOR CONCRETE"
1620      READ,RHO
1630      WEIGHT=RHO*XLENGTH*BEE*TEE
1640      GO TO 50
1650 040 PRINT,"ENTER WEIGHT IN LBS."
1660      READ,WEIGHT
1670 050 FREQ=(XMODULUS/(C*WEIGHT))**0.5
1680      VELOCITY=FREQ*XLENGTH
1690      PRINT,"    C        WEIGHT  LENGTH     B        T      MODULUS
1700& FREQUENCY VELOCITY"
1710      PRINT,"                 LBS.    FEET     FEET     FEET      PSI.
1720&     HZ       FT/SEC"
1730      PRINT 60,C,WEIGHT,XLENGTH,BEE,TEE,XMODULUS,FREQ,VELOCITY
1740      PRINT,
1750      PRINT,
1760 060 FORMAT(F8.6,F10.1,F7.1,F9.1,F9.1,F10.1,F9.1,F9.1)
1770      GO TO 070
1780 080 STOP
1790      END

READY
```

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Alexander, A. Michel
Development of procedures for nondestructive testing of concrete structures : Report 3 : feasibility of impact technique for making resonant frequency measurements / by A. Michel Alexander (Structures Laboratory, U.S. Army Engineer Waterways Experiment Station). -- Vicksburg, Miss. : The Station ; Springfield, Va. : available from NTIS, 1981.
28, [3] p. : ill. ; 27 cm. -- (Miscellaneous paper / U.S. Army Engineer Waterways Experiment Station ; C-77-11, Report 3)
Cover title.
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1. Concrete--Testing. 2. Concrete construction. 3. Non-destructive tests. 4. Structural dynamics. I. United States. Army. Corps of Engineers. Office of

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